Novel Energy Efficient Schemes for Wireless Sensor Networks Utilizing Mobile Sensors

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Abstract. Wireless sensor networks (WSNs) facilitate many applications in different fields and are well-known in both academic and industrial areas. The networks mainly include sensors, networking parts and a data processing center to collect data for a variety of purposes. However, the energy consumption problem in the networks is always a critical problem that many researchers are looking for good solutions. In this paper, we propose a data collection method that uses mobile sensors attached with bigger energy storages to collect data from static sensors. In addition, we propose a hybrid energy harvesting scheme to harvest energy from ambient environments to support static sensors to prolong the network lifetime. Some algorithms are provided to support the networks either with data collection or harvesting energy. We outline various possibilities for powering the gadgets with solar and RF energy gathering. In particular, all the circuits that are constructed using mathematical equations are offered. All of the network possibilities are clarified using simulation and experimental results. The outcomes are encouraging and useful.

Keywords: Wireless sensor networks · Mobile sensors · Data collection · Energy harvesting · Radio frequency (RF) · Solar energy · Energy efficiency

1 Introduction

1.1 Motivation

Traditionally, wireless sensor networks (WSNs) include a lot of sensors for measuring sensing data from ambient environments. The sensors are small, inexpensive and have limited capacity of communication and energy storage [1, 2]. They collect sensory data to be transferred to a base station (BS) or a data center. They operate in the networks

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until they deplete all the energy storage in their pre-charge batteries. The networks may stop working if some sensors disconnected to each other. Hence, energy saving in such networks is always a critical issue that needs to improve [3, 4].

There are many energy efficient mechanisms to improve the network lifetime based on different points. Many data collection methods are proposed to save energy consumption for the networks [5–8]. In clustered WSNs, cluster heads (CHs) can help non-CH sensors saving energy from sending directly to the BS. In addition, the role of being CHs can be changed to balance energy storage for sensors [5]. In tree-based WSNs, sensors are connected as tree with the root as the BS. The multi-hop routing communication through the tree can significantly save energy due to the short communication range between sensors [6]. Random walk routing [7] and Gossiping [4, 8] sensing data in WSNs also support energy saving and balancing problems in the networks that can prolong the network lifetime.

Data processing techniques are also useful to support energy saving in WSNs. Sensing data in almost applications are usually high correlated or compressible that can be sampled or compressed to be a certain number of measurements, instead of being as raw data. There are many techniques that can support to process data in the networks. A lot of results using frequency domains such as Wavelet or discrete cosine transform (DCT) to compress data [9, 10]. Compressed sensing (CS) techniques are also combined to routing methods to reduce data transmission in WSNs [11, 12]. The smaller the number of the sending measurements, the lower the energy consumption from sensors or the networks. Hence, the network lifetime can be improved significantly.

However, all of the efforts also have some limited capacity to solve the energy saving problems. The networks need to be more active to operate long and to be more suitable to many applications while the demand for the network services is increasing. Currently, energy harvesting techniques are proposed to support the network directly. The sensors can harvest energy from their surrounding environments, since there are energy resources available right at the sensing areas. This could be a promising point for now and the future development of WSNs.

1.2 Related Work

Traditional WSNs collect data based on different topologies [4–8]. However, static sensors with very limited capacities cannot deal with long distance communication and also long-time operation demand. Hence, mobile sensors are often deployed in a sensing area to either collect data or support the static sensors. Normally, static sensors measure data from the fields and send the data to the mobile ones. Finally, the data are sent to the BS in long communication ranges by the mobile sensors [13, 14]. In different scenarios, to save energy, mobile sensors do not move to all positions in a sensing field, the only move in some certain regions and share their collected data to each other, then finally send the whole data to the BS [15–17]. Based on the previous work, the mobile sensor can save significant energy for static sensors, and definitely prolong the network lifetime.

Energy harvesting methods have been widely used in a variety of systems depending on the available natural resources, such as wind, solar, RF, thermal, flow (wind, hydro), mechanical (vibration, pressure), human (activity, physiological), etc. [18–20]. These resources can be categorized as predictable and controlled or not. The most effective ways to provide systems that require more energy or function depending on the harvested energy may be found by selecting appropriate energy harvesting technologies based on the characteristics of the various resources.

Since the sensors in WSNs are normally very small and they do not spend much energy, it seems quite possible to harvest energy from ambient environments. Depending on specific sensing fields, the sensors can harvest energy from different resources, such as RF, solar, thermal or wind. In papers [16, 17], the authors provide possible energy consumptions for sensors in different status. Based on the levels, we can design energy harvesting models to support the sensors effectively. In papers [18–21], different resources are exploited separately that provide significant energy for the sensors. Each resource has either advantages or disadvantages that depend on specific conditions. Hence, choosing suitable resources to harvest energy is important to support static sensors.

Based on the ideas of previous work, including the motivation, we propose a hybrid energy harvesting mechanism that can combine energy harvested from different resources. In our work, solar and RF energy are collected and then combined to charge sensor batteries. The RF energy may not provide much energy but quite stable while the solar resource is only available in day time but unlimited. We either propose data collection algorithms or energy harvesting algorithms for the networks. New system models are provided in our work. Circuits are designed and associated with simulation results to clarify the models.

The rest of the paper is organized as follows. Section 2 provides system models and problem formulation. Section 3 addresses details of our algorithms with the energy harvesting methods, including circuit designs. Some simulation results are provided in Sect. 4 to clarify our proposed problems. Finally, conclusions and future work are provided in Sect. 5.

2 System Model and Problem Formulation

2.1 System Model

We assume that many static sensors are randomly deployed in a sensing area that needs to be observed. The sensors can communicate wirelessly to each other within their communication ranges, denoted as R_c. They measure sensing data to be sent to a data processing center or a base-station (BS). In order to support the static sensors, a certain number of mobile sensors are also randomly deployed in the sensing field. They have higher profiles compared to the static sensors to deal with longer communication ranges. In addition, they are expected to support the static sensors with either data collection or energy supply. The network is illustrated in Fig. 1.

The mobile sensors are designed with circuits that can harvest energy from solar and RF from the sensing field. All the energy collected is combined to charge the batteries attached to them. The mobile sensors later can either collect data from sensor nodes or transmit energy to static sensor nodes. Based on this model, the mobile sensors can save energy for static sensors and share their harvested energy to supply the sensors.

Static sensors are also designed to harvest energy from the ambient environments. However, their profile is small and inexpensive. Hence, it would be better if they can receive directly energy from mobile sensors in short communication distances.

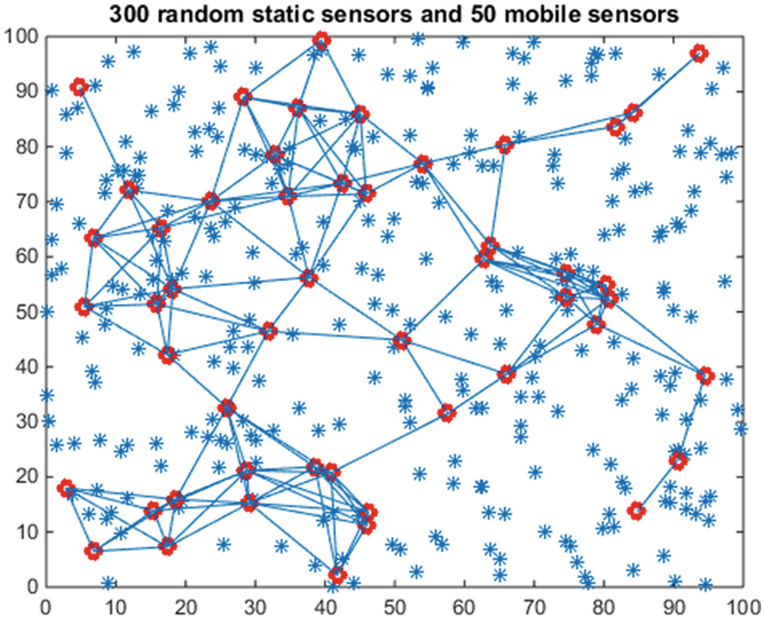


Fig. 1. A certain number of static sensors (in blue) and mobile sensors (in red) are deployed randomly in a sensing area for monitoring purposes.

2.2 Energy Model

Almost energy consumption of sensors focuses on transmitting, receiving and processing data, as shown in Table 1. Hence, different operating modes are designed appropriately to save energy for the sensors. Normally, K-bit packets are considered and associated with the transmitting distances (d) in such network to calculate energy consumption for static sensors as follows.

$$E_{TX}(K,d)_{static} = \begin{cases} E_{elec}K + \epsilon_{fs}Kd^2, d < d_o \\ E_{elec}K + \epsilon_{amp}Kd^4, d \geq d_o \end{cases}, \tag{1}$$

$$E_{RX}(K)_{static} = E_{elec}K \tag{2}$$

where E_{elec} is the energy necessary for sending 1-bit and E_{RX} presents the energy usage to receive data. ϵ_{fs} and ϵ_{amp} are the amplified power in the radio model. d_0 is the threshold obtained using Eq. (3) as follows.

$$d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{amp}}} \tag{3}$$

The energy consumption models for the mobile sensors include receiving data from static sensors and transmitting data to the BS that are also calculated as follows.

$$E_{RX}(K)_{mobile} = E_{elec}K \tag{4}$$

$$E_{TX}(K, d)_{mobile} = \begin{cases} E_{elec}K + \epsilon_{fs}Kd^2, d < d_o \\ E_{elec}K + \epsilon_{amp}Kd^4, d \geq d_o \end{cases} \tag{5}$$

In addition, when the mobile sensors exchange data with each other, the energy model can be calculated as follows.

$$E_{RX}(K)_{mobile} = E_{elec}KM \tag{6}$$

where, M is the convergence time that the mobile sensors exchange completely their data with each other.

Table 1. Energy consumption in a MICA2 sensor nodes with a CC1000 transceiver in different modes that can be flexibly scheduled.

Mode	Time	Energy consumption
Sleep	……	90 µW
Initiate radio	0.35 ms	18 mW
Turn radio	1.50 ms	3 mW
Switch Tx/Rx	0.25 ms	45 µW
Receive 1 byte	0.4 ms	45 µW
Transmit 1 byte	0.4 ms	606060W

2.3 Data Collection Method

In this paper, we propose an algorithm that can support either static sensors or mobile sensors to collect data in WSNs with energy saving manners. With the mobile collaborations, each mobile sensor can be considered as a distributed one. One mobile sensor can have all the data from all static sensors if it has enough time for exchanging data. This point can support the network in case of some mobile sensors become failure, the others can transmit data to the BS with all data from the network. The data collection algorithm is addressed as follows.

Algorithm 1: Hybrid data collection for mobile sensors to support WSNs

Phase 1: Initialization

1. *N sensors are randomly deployed in a sensing area;*
2. *M mobile sensors are also randomly deployed in the sensing area;*

3. *All the sensors can communicate wirelessly within a communication range* R_c;

Phase 2: Data communications between the sensors

4. *M mobile sensors move to the sensing area among static sensors;*
5. *N static sensors transmit their sensing data to mobile sensors within their* R_c;

Phase 3: Exchange data between mobile sensors

6. *M mobile sensors may have different number of collected measurements from static sensors;*
7. *M mobile sensors share the collected data to each other within their* R_c;

Phase 4: Sending data to the Base-station (BS)

8. *After a convergence time (T), each mobile sensor can have all sensing data from the network;*
9. *M mobile sensors finally forward the whole data to the BS.*

2.4 Energy Harvesting Scheme

In this paper, we propose that either static sensors or mobile sensors can harvest energy from ambient environments. However, the static sensors are small that cannot guarantee to collect sufficient energy to supply themselves. Hence, the mobile sensors with higher profiles can harvest and transmit energy wirelessly to support the static sensors.

Table 2 provides possible energy that can be harvested from ambient environments. Based on the table, we choose to combine energy from solar and RF into mobile sensors.

Table 2. Possible energy harvesting from different resources.

Energy sources	Conditions	Performance
Solar	Outdoor	$7500\ \mu W/cm^2$
Solar	Indoor	$100\ \mu W/cm^2$
RF	Wi-Fi	$0.001\ \mu W/cm^2$
RF	GSM	$0.1\ \mu W/cm^2$
Vibration	$1\ m/s^2$	$100\ \mu W/cm^3$
Thermal	$\Delta T = 5\ ^0C$	$60\ \mu W/cm^2$

We propose a scheme to harvest energy for either static sensors or mobile sensors as shown in Fig. 2. The steps for designing the harvesting system are addressed as follows.

Algorithm 2: Hybrid energy harvesting Solar and RF resources to power WSNs

Phase 1: Initialization

1. *N sensors are designed to be able to harvest Solar and RF;*
2. *M mobile sensors are designed to be able to harvest Solar and RF;*
3. *Assume that the all conditions that support the process without loss or disturbance.*

Phase 2: Solar Energy Harvesting

4. *M mobile sensors can harvest energy from solar separately;*
5. *N static sensors can harvest energy from solar separately;*

Phase 3: RF Energy Harvesting

6. *N static sensors can harvest energy from RF separately;*
7. *M mobile sensors can harvest energy from RF separately;*

Phase 4: Combine RF and Solar energy to power WSNs

8. *Design circuits to combine both the energy resources;*
9. *Test and compare in different conditions;*
10. *Evaluate, stabilize the hybrid system.*

3 Circuit Design for the Harvesting Systems

The Fig. 3 shows the detailed diagram of the proposal. For each energy source, we will have a separate method and technique to harvest, the ultimate goal is to create a DC power source to put into the charger to charge the battery. In the Fig. 3, the solar energy source uses the MPPT algorithm and the boost converter to raise the voltage to the required level of 18.5V. The RF energy source is harvested from the surrounding environment at the 900MHz frequency range, then through the converter circuits to obtain a DC voltage of 5V corresponding to 5 stages connected in series. The detailed design of the system components is described in the following sequence.

3.1 RF Energy Harvesting

Impendence matching: In this paper, we use inductor (L) and capacitor (C) elements to perform impedance matching.

We assume the design requirement of an impedance matching circuit with source impedance $Z_S = 50\ \Omega$, load impedance $Z_L = 60 - 45j\ (\Omega)$, line impedance $Z_0 = 50\ \Omega$, operating at 900MHz. Parameters L and C are calculated based on the Smith graph.

We choose S-Parameters with a hop of 0.1 GHz, starting frequency of 0.1 GHz, and ending frequency of 2 GHz as shown in Fig. 4.

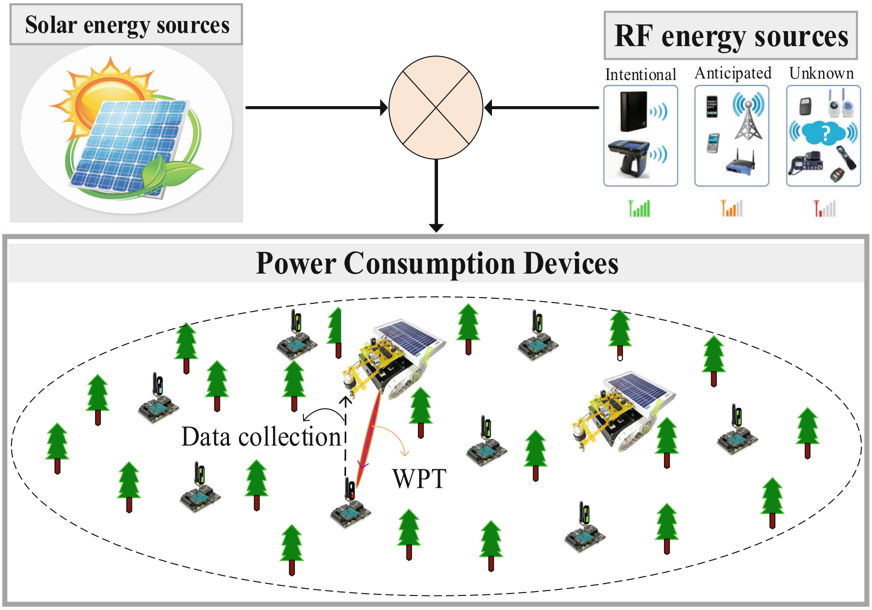


Fig. 2. A hybrid harvesting design to supply static sensor nodes and mobile sensors.

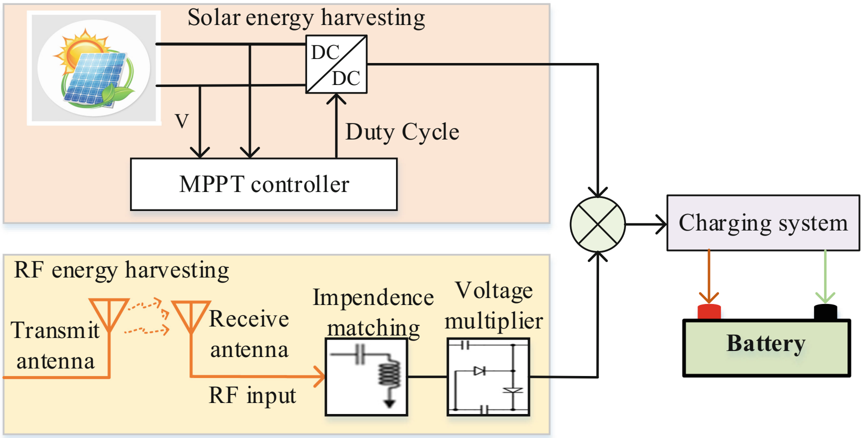


Fig. 3. Proposed energy harvesting system

Voltage multiplier: In Fig. 5, the RF energy through the impedance matching circuit, this energy will go to the next circuit called rectifiers, to convert from AC source to DC source. The output voltage depends on the number of stages in the circuit. In this paper, we use 5 stages connected in series, and the output voltages are different from each state.

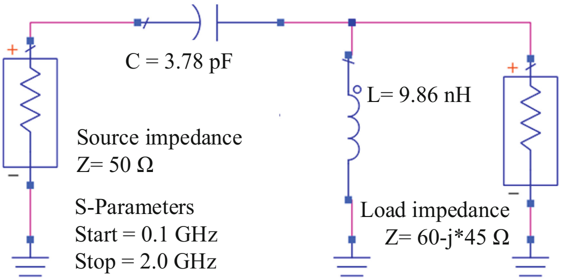


Fig. 4. Impedance matching circuit design

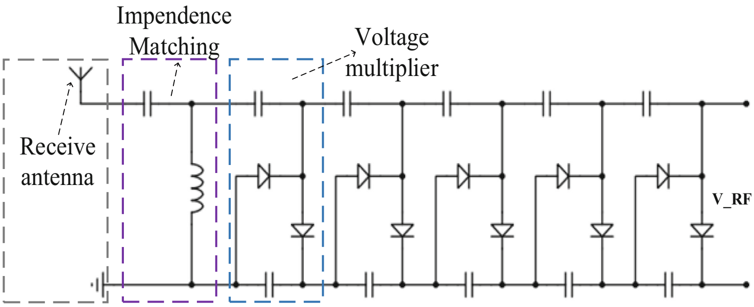


Fig. 5. The full multistage voltage multiplier circuit

3.2 Solar Energy Harvesting

The process of building and simulating the MPPT algorithm is shown in Fig. 6. In Fig. 7a, the relationship between output current and voltage of the solar harvesting system using the MPPT algorithm is presented. The graph shows that thanks to the MPPT algorithm, the current only fluctuates in the range from 0.25 A to 0.3 A and the output voltage always fluctuates in the range from 18 V to 20 V.

In Fig. 7b shows the relationship between voltage and maximum output power of the solar harvesting system, the power is in the range from 4.6 W to 5 W. However, the disadvantage of the solar energy system is that it is highly dependent on the surrounding environmental conditions. Therefore, we need to combine with another energy source that is less dependent on environmental conditions, which is RF energy.

3.3 Charging System

We designed the detailed charging circuit diagram as shown in Fig. 8, one of the important elements of this charging circuit is the LM317. LM317 is a voltage regulator IC. Pin 1 (ADJ) of the IC is the control pin used to control the charging voltage. Pin 2 (VO) is the output pin where the charging voltage appears. Pin 3 (VI) is the input pin to which the regulated DC supply is supplied. The output voltage can be adjusted to nearly 40 V. The voltage regulation of the LM317 is in the range from 1.25 V to 37 V, the maximum output current is 1.5 A, and the internal resistance is as small as 0.05 Ω.

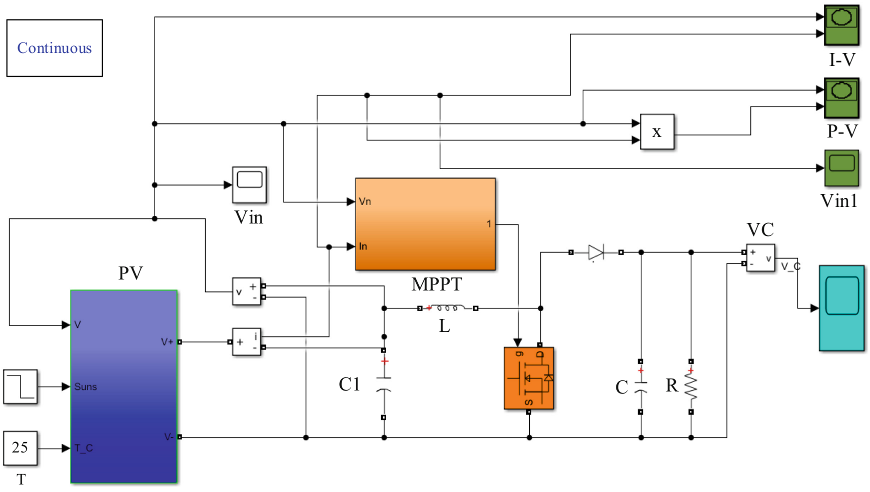
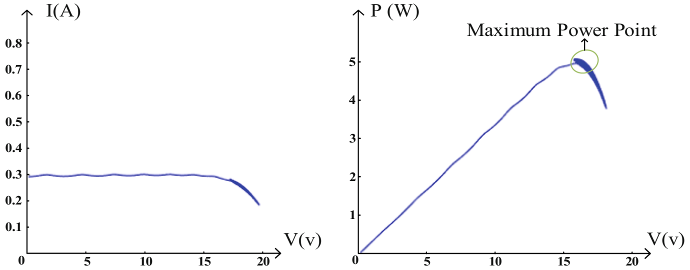


Fig. 6. Harvest solar energy using the MPPT algorithm



(a) (b)

Fig. 7. The output of solar harvester circuit using MPPT algorithm.

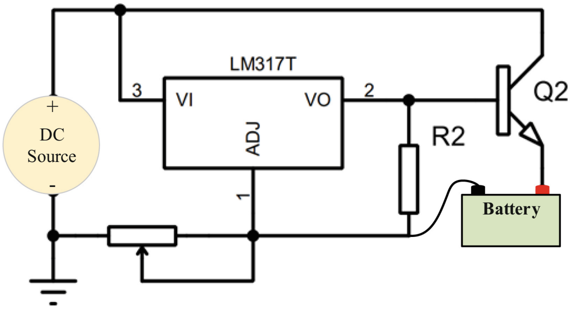


Fig. 8. Proposed charging system

Because the maximum output current of the LM317 is only 1.5 A. so we need to use transistor Q2 to amplify the current, we have a higher charging current to help the battery charge process faster. The regulation of charging voltage and charging current is dependent on rheostat and resistor R_2.

4 Simulation Results

In this section, we work on different schemes with energy efficient manners for WSNs including data collection and energy harvesting methods for mobile sensors.

4.1 Data Collection Methods

As shown in Fig. 9, there are 20 mobile sensors are randomly deployed in a square sensing area to collect data from 500 static sensors. The sensors have a limited communication range as R_c that also can be changed to be able to achieve different results. In our simulations, for simplicity, we assume there are no obstacles, no loss. Hence, the power consumption is only based on the distances between sensors.

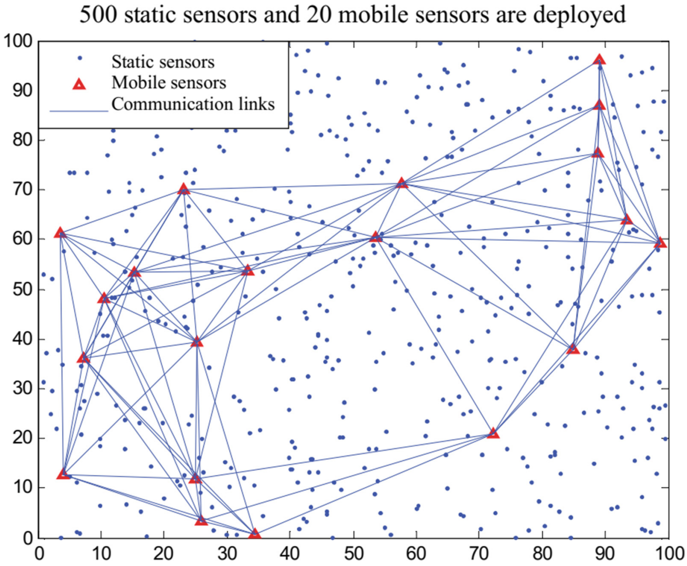


Fig. 9. 20 mobile sensors with communication range Rc = 50 [unit] are deployed to support 500 static sensors in a square sensing area of 100*100 [unit].

As mentioned in Algorithm 1, Fig. 10 shows the convergence time for exchanging data between the mobile sensors. As shown in the figure, as the communication range R_c increased, the convergence time is reduced. It means that increasing the connections between mobile sensors can make the exchange data processes go faster. Regarding the power consumption for the networks, Fig. 11 provides the total power consumption for the network to collect data.

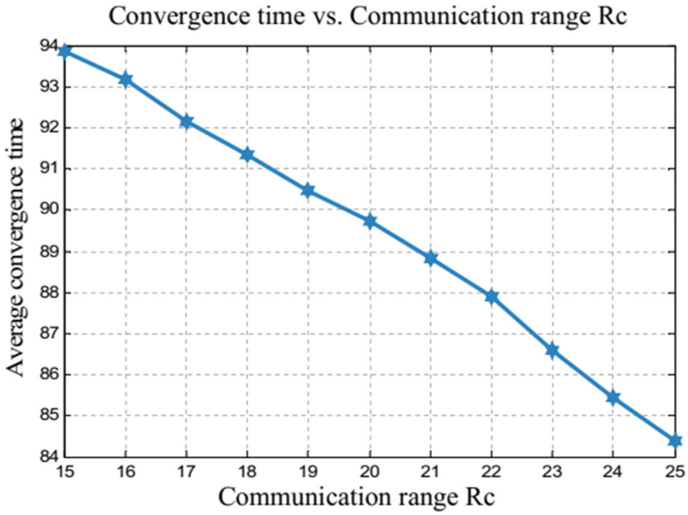


Fig. 10. The convergence time for mobile sensors exchanging data completely with different communication ranges in a square sensing area of 100*100 [unit].

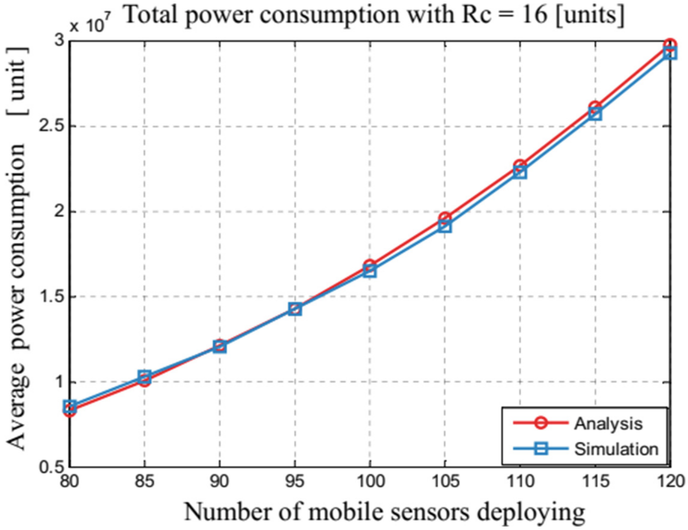


Fig. 11. The total power consumption (energy consumption) for data transmission in a square sensing area of 100*100 [unit].

4.2 Charging System for Mobile Sensors

Unlike sensor nodes, our mobile sensors use an energy harvesting system that combines solar energy and RF energy. Because the mobile sensors require quite high charging current and charging voltage, so each RF power source could not be enough to supply. Solar energy is highly dependent on the surrounding electrical conditions, so we need to hybridize these two sources together to charge the mobile sensor battery. Therefore, the DC power source on the diagram in Fig. 12 will now be replaced by the output voltage of the energy harvesting system hybrid RF—Solar energy as shown in Fig. 12.

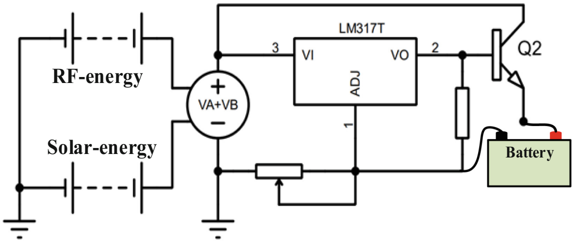


Fig. 12. Charging system for mobile sensors

The voltage after passing through the output of the charging system will be 20 V and the current is 6.8 A.

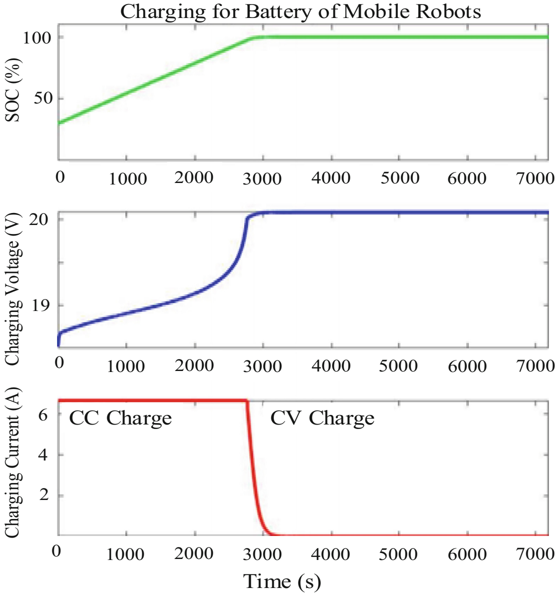


Fig. 13. The battery charging process of mobile sensors

The charging process of devices in the network is shown in Fig. 13. With the mobile sensor, we use a battery with a capacity of 7.66 Ah, the charging current is 6.8 A, the charging voltage is 20 V, and starts to recharge when the SoC of the battery drops to 30%. The charging process is shown in Fig. 13. The battery charging process goes through two stages, phase one from time t = 0 s to time t = 2600 s, the battery is charged by a current source (CC charge). When SoC = 80%, the battery goes to the second stage. That is, from the time interval t = 2600 s to 3000 s as shown in the Fig. 13. Charging phase by a voltage source (CV charge) for the SoC of the battery to reach 100%.

5 Conclusion and Future Work

In this paper, we propose an energy efficient framework for mobile sensors to support WSNs to deal with energy saving problems. Data collection methods are proposed for both the mobile sensors and static sensors. Simulation results are provided to clarify our data collection algorithm. Regarding the energy harvesting problems, we also have proposed an efficient energy collection system for mobile sensors and static sensor nodes. We have detailed design issues with devices with different power consumption to use the power accordingly. Our proposed system can generate a fairly high charging current I = 6.8 A. Therefore, it is possible to reduce the charging time for the battery significantly. When the SoC (State of Charge) parameter of the battery drops to 30%, the system will activate the charging process for the Battery. Therefore, the system work can prolong the working time for the devices in the network.

In our future work, the problems should be presented with real devices in both data collection and energy harvesting. Optimization problems should be defined and solved to support the network to be able to provide the best performance.

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